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16. ABSTRACT

The report discusses parameters used to measure and describe noise. It presents and discusses a noise emission model for automobiles and a free field noise dispersion model for predicting L_{eq}. Noise barriers are discussed at length. A formal nomograph method is presented for predicting barrier effectiveness against truck noise peaks. A computer method is also given for predicting barrier effectiveness. There are ancillary notes on noise reflections, ground effects and atmospheric effects.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

January 1976

FHWA No. A-8-2
TL No. 656316

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

TRAFFIC NOISE NEAR HIGHWAYS

Study made by . . . . Enviro-Chemical Branch

Under the Supervision of . . . . Earl C. Shirley

Principal Investigator . . . . Walter A. Winter

Report Prepared by . . . . Walter A. Winter

Very truly yours,

George A Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment

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ACKNOWLEDGEMENTS

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The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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INTRODUCTION

The California Department of Transportation has been active in the study of highway related noise since 1954. At that time, freeways were considered a marvel of the time and traffic noise was not generally realized to be a problem.

Today freeways crisscross most urban areas and the public has become acutely aware of the noise that is generated by vehicles using the freeways. This awareness was first manifested to highway departments in the form of complaints. More recently, vehicle noise has become a focal point in community resistance to the construction of new highways.

This research project was begun in 1966 in response to numerous public complaints of vehicle noise. The objectives of the research project were to develop better methods of evaluating, predicting, and controlling traffic noise near highways. In 1969, the project was expanded to include evaluation of both the traffic noise source and its effects near highways. The project's first interim report was published in 1968 (1). It laid the foundation for traffic noise analysis within California. A second interim report was published in 1973 (2) and presented a formal method of measuring highway noise. It also discussed oise barriers. This report concludes the project. It formalizes he barrier prediction methodology previously presented and lays foundation for a more rigorous approach to the prediction of sportation noise.

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majority of the report is dedicated to the blocking of noise transmission paths by noise barriers. There are ancillary notes on noise reflections, ground and atmospheric effects as well as recommendations for further study.

CONCLUSIONS AND RECOMMENDATIONS

Noise Parameters

It was found impractical to use a single number parameter as a complete descriptor of the noise environment. The equivalent noise level (L_{eq}) was a good descriptor of overall or "average" noise, but it did not correlate as well with annoyance as did maximum levels (L_{max}). It was decided that both L_{eq} and L_{max} should be used as descriptors of the noise environment, and that the frequency of occurrence of the maximum levels may also be of concern.

Noise Emission Models

A generalized noise source model based on drive-by tests and the literature was developed. It was found necessary to use two equations in the model. The first equation represents tires and other nonpower plant oriented noise sources. The second equation represents power plant oriented noise sources. The sum of these equations closely fits experimental data for vehicle speeds from idle to 75 miles per hour. This type of modeling will become more and more necessary in the future as the onus for noise reduction alternates between the automob[ile] industry and the tire manufacturers.

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Propagation Models

The California Maximum Level Propagation Model has been in the literature for many years. An L_{eq} based propagation model was recently developed. Although it was developed independently, other investigators are working with the same basic equation (3,4).

Barrier Attenuation

The majority of the research effort went into the study of traffic noise barriers. A method of predicting the effectiveness of barriers in attenuating maximum noise levels was developed. The attenuation in terms of L_{eq} was not studied although it is recommended that this work be done in the near future.

Additional Attenuations

Ground effects, reflections, atmospherics and other subtle attenuation phenomena were not studied. It is believed that research in these areas is not yet adequate. However, these are subtle phenomena and will require a great deal of sophistication to properly research.

Recommended Additional Research

There remain several areas in need of additional study. These areas include vehicle noise emissions, barrier diffractions, and noise scattering. These subjects are reiterated later under "Recommendations for Future Work".

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IMPLEMENTATION

The peak noise level barrier attenuation nomograph and computer program are now in use in designing attenuation facilities to comply with Section 216 of the California streets and highways code which established 50 dBA as the maximum noise limit in school classrooms.

The vehicle noise propagation model can be used to predict L_{eq} levels for virtually any transportation facility for which individual vehicle noise emission levels, vehicle speed and vehicle volumes are known.

PARAMETERS FOR NOISE DESCRIPTION

Frequency Content of Noises

The human ear is selective in the sound frequencies that it can hear. Some method must be used to account for this before sound level values can be correlated to human annoyance.

Use of the A weighting network is now well established as the method of compensating for the ear's frequency sensitivity when performing environmental noise studies. A weighted sound levels were used throughout this study except where spectral analyses were performed. The presence of A weighting is implied throughout this discussion unless otherwise noted. This point is reiterated under "Predicting An L_{eq}".

Maximum Levels

One of the first quantitative descriptors of transportation noise was the maximum noise level. This descriptor is still in use by

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Caltrans and is the basis for much of the current noise legislation. Maximum levels are easy to model, they correlate well with annoyance, they are easy to conceptualize and measure and they are a suitable base for legislation and enforcement. Their major disadvantage is that, by themselves, they do not take into account the number of occurrences.

Time Varied Noise Parameters

Because of this disadvantage, the L_{10} methodology was developed to replace peaks. The L_{10} is a noise level that is exceeded 10% of the time. It proved an adequate descriptor for high volume highways; however, it proved difficult to measure and very difficult to predict. It proved not applicable when comparing noise sources with different time variances (i.e. train noise vs. aircraft noise vs. highway noise). The L_{10} also fell down as a descriptor of traffic noise on low volume highways. The methods now coming into favor are based on the L_{eq} which is, in turn, based on the average A weighted acoustical energy intensity over a given time period. The L_{eq} is much easier to predict and it can be used in environments where noise from many different sources are present. The L_{eq} is considered an excellent parameter for describing the average noise level or "background" noise in a given environment.

However, the L_{eq} has not correlated well with annoyance. Noise that occurs as peaks or defineable discrete happenings has proved more annoying than the same amount of noise energy spread over a long period of time. Therefore, there is currently a trend towards parameters that take into account the variance of the noise. One of these parameters is the L_{np} or noise pollution level. This is derived by adding to the L_{eq} a factor times the standard deviation of the noise level. The noise

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pollution level has proven to correlate better than the L_{eq} with annoyance. However, it is doubtful if any one numerical parameter can be developed that would truly have a one for one relationship with annoyance under all cases. Even if such a parameter were developed, it is highly doubtful that the meaning of such a parameter could be conveyed easily to laymen.

Combined Noise Parameters

It is suggested that the noise environment be described in terms of L_{eq} and maximum levels.

Combined, these parameters do a good job of describing the noise environment and they are easy to measure, easy to predict and conceptually simple.

PROPAGATION MODELING

Maximum Levels

The maximum level is the easiest noise parameter to model. In most cases one must understand the maximum levels before more complex parameters can be developed. Diesel trucks are normally the noisiest vehicles that are found on todays highways. They are therefore, the source that is used to model maximum noises.

There are several steps in maximum noise modeling. The first step is to determine the amount of noise that the source produces. This is usually expressed as the level measured 50 feet from the source. This step is referred to as "emissions modeling". The second step is to determine the point in the pass-by of the source that gives the highest noise level at

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the receiver. This is usually (but not always) the closest point of the pass-by or the distance from the receiver to the traveled way. Knowing the level at 50 feet and the minimum distance from the source to the receiver, the maximum noise level can be calculated by using the inverse square law which will be discussed later. Normally these steps give an adequate model of maximum noises when the receiver is close to the source and there are no obstructions between the two.

To do it right, however, it is necessary to subtract any attenuations that may affect the propagation of the noise, such as noise barriers, ground effects, or atmospheric effects. Next, enhancements should be added such as reflections off hard surfaces and lastly, the background noise should be added. When predicting maximum levels close to the highway facility, truck maxima normally are so much higher than the prevailing background that the background can be ignored. However, the background can seldom be ignored when predicting maximum levels at locations several hundred feet from a highway facility or even predicting maximum levels fairly close to a freeway flowing near capacity.

Inverse Square Law

The inverse square law is used to predict the level received from a source located a given distance from a receiver (5). The basic assumption is that energy in the form of acoustical watts radiates from the source in a spherical manner. The source can be pictured as being the center of a sphere and the receiver as being a point on the surface of some concentric sphere. The energy at the receiver (I_r) can be calculated in terms of watts per unit area by dividing the energy of the source by the surface area of the sphere. This is shown in the equation (1).

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$$I_r = \frac{E_s}{4\pi d^2} \qquad (1)$$

where

I_r = intensity at the receiver in acoustical watts per square meter

E_s = energy of the source in acoustical watts

d = distance from source to receiver in meters.

The acoustic intensity can be calculated from the sound level by equation (2) (see Appendix A).

$$I = 10^{\left(\frac{L}{10} - 12\right)} = \text{Antilog}\left(\frac{L}{10} - 12\right) \qquad (2)$$

where

I = sound intensity in acoustical watts per square meter

L = the sound level in dB.

It is difficult or even impossible to measure the energy of the source directly. Therefore, measurements are normally made at a standard distance and the energy of the source is inferred. This inferred energy can than be used with equation (1) to predict the acoustic intensity and therefore the level at the receiver which is a known distance away.

Below is an example of the mathematics involved. This is essentially a derivation of the inverse square law and shows that there is a 6 decibel reduction per doubling of the distance between a source and a receiver.

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To start, the noise level of the source must be measured at a given distance. This is usually the dBA at 50 feet. This level is converted to intensity using equation (2). The energy of the source can be calculated by transposing equation (1) to:

$$E_s = 4\pi I_r d^2$$

when the meters to feet conversion is applied and 50 feet is assumed, the two equations can be combined to give:

$$E_s = 2919 \text{ Antilog } \left(\frac{L_{ref}}{10} - 12\right) \tag{3}$$

where

L_{ref} = Level at 50 feet (15 m).

Now the intensity at the receiver can be calculated using equation (1). With the proper conversion factors, equation (1) becomes equation (4).

$$I_r = \frac{0.8566\ E_s}{d^2} \tag{4}$$

where

d = distance in feet from source to receiver.

It can now be seen that the intensity at the receiver is a function of the source strength and the inverse square of the distance.

The intensity can now be converted to a level using:

$$L = 10 \text{ Log } \left(\frac{I}{10^{-12}}\right) \tag{5}$$

which can also be written:

$$L = 10 \text{ Log } (I) + 120 \tag{6}$$

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Combining all of these steps gives:

$$L_r = L_{ref} + 20 \text{ Log } \left(\frac{D_{ref}}{D_r}\right) \quad (7)$$

where

L_r = level at the receiver

D_r = distance from the source to the receiver

D_{ref} = reference distance (normally 50 feet)

L_{ref} = level at distance D_{ref}.

Inserting a few values for the reference distance and the distance to the receiver shows that the level rolls off at 6 dB per doubling of distance.

Predicting an L_{eq}

The L_{eq} is based on the average perceived acoustical energy received at a point over a given period of time. Noises in the very low frequencies and very high frequencies are not perceptible to the human ear. The A weighting network was developed to compensate for this and is used in all L_{eq} calculations. If emission modeling is done in terms of dBA, the A weighting network will correct for the loss of hearing in the lower and higher frequencies and this correction will automatically be carried throughout the calculations. This report considers acoustical energy in terms of watts; however, the watts used will not be true watts but will reflect the A weighting network. Therefore "equivalent watts" or "equivalents" will be used as the energy term to recognize the effect of A weighting.

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There are two methods of L_{eq} modeling; they are very similar and yet, there are some differences in the mathematics. The first method is to determine the average intensity in equivalent watts per square meter for each source over the measurement period; summarize those averages to obtain a mean intensity and then convert this to the L_{eq} using the following equations (5):

$$I = 10^{(\frac{L}{10} - 12)} = \text{Antilog}_{10}(\frac{L}{10} - 12) \qquad (8)$$

$$L = 10 \text{ Log}_{10}(\frac{I}{10^{-12}}) = 120 + 10 \text{ Log}_{10}(I) \qquad (9)$$

where:

I = intensity in equivalent watts/square meter

L = sound level in dB

10^{-12} = reference wattage per square meter.

Note: If mean intensity ($\bar{I}$) is substituted for I then L_{eq} can be substituted for L.

The second method is to determine the equivalent seconds of noise attributable to each source. The equivalent second is the intensity received from the source integrated over the time, in seconds, that it was received. These equivalent seconds are then summarized for all sources. The total is divided by the number of seconds in the period to give the average, or mean, intensity. This mean is then converted to the L_{eq} using the same equation as was used in the first method [equation (9)].

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L_{eq} Based Traffic Noise Models

In working with traffic noise models, it is somewhat easier to use the second method or the summarization of watt seconds.

First the background noise is determined. If this is known in L_{eq} terms, then the equivalent watt seconds can be determined using equation 10:

$$I_{sec} = \text{Antilog}_{10} \left(\frac{L_{eq}}{10} - 12\right) T \qquad (10)$$

where

I_{sec} = equivalent watts per square meter seconds

T = time in seconds.

Normally, a one hour or 3,600 second time period is used. If there are periodic noises, then the same equation can be used. The number of seconds during the time period that the periodic noise is received can be used as the time parameter in the above equation. The resultant equivalent seconds can be added to the equivalent seconds of the normal background.

Transportation Noise

One type of noise source should be studied at a time. If a freeway is being studied then automobile traffic on one lane can be considered separately from truck traffic on the same lane. Each lane can be considered separately or lanes can be lumped. There is an obvious trade-off between the complexity of the calculation and the accuracy of the results.

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Taking one source at a time, the equivalent power of that source is determined. This is the total number of equivalent watts that the source produces assuming the source is omni-directional. If this assumption cannot be made, then the equivalent power must be corrected for directionality.

Next, the equivalent watt seconds per pass-by for that source is predicted. All enhancements (reflection, etc.) and attenuations (ground effect, acoustical impedance of the air, barriers, etc.) must also be considered. The equivalent seconds per pass-by is then multiplied by the number of pass-bys expected for that particular type of noise source. The same calculation is performed for all other types of transient noise sources and the results are summed to obtain the total equivalent watt seconds due to transient noise.

The watt seconds from background and periodic noises are added to this total which, in turn, is divided by the number of seconds in the summarization period (normally 3600) to obtain the average equivalent watts for the period. This, in turn, is converted to the L_{eq} using equation (9) described above.

Noise Models

Noise models are broken into two categories: noise emission models and noise propagation models. In performing research work, it is important that these two types of models be studied separately; however, combining them can greatly simplify design computations.

Emission Models

The goal of the emission models is to determine the equivalent wattage of specific sources. In order to do this, the dBA level attributable to the source is measured at a given distance from

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the source. This dBA level is converted to equivalent watts per square meter. The equivalent wattage of the source is then inferred by determining how many equivalent watts it would take to "project" the measured watts per square meter from the source to the measurement point. Equations (12) or (13) are used for this purpose.

$$E_s = 4\pi d^2 I \qquad (11)$$

where

E_s = A weighted equivalent wattage at the source

d = distance from the source to the monitor (normally 50').

Assuming the distance = 50' (15.24 meters):

$$E_s = 2919\ I \qquad (12)$$

Combining equations 8 and 12;

$$E_s = 2919\ \text{Antilog}_{10}\left(\frac{L}{10} - 12\right) \qquad (13)$$

Determining the dBA level at 50 feet is a study unto itself and will be discussed elsewhere. Suffice it to say that a truck at normal highway speeds will produce about 86 dBA as measured at 50 feet. Using equation (13) it can be shown that such a truck produces about 1.16 equivalent watts at the source. If we assume that a car produces 70 dBA at 50 feet when it is driving by at 55 mph, then the calculations show that the car produces about 0.03 equivalent watts at that speed.

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One major assumption made here is that vehicles are essentially omni-directional noise producers. There is adequate research data to show that this assumption is not true; however, the conclusion reached by most investigators is that the A weighted noise from automobiles and trucks is close enough to being omni-directional to be considered as such for noise modeling purposes (9). It remains to be seen if this assumption holds as noise modeling technique becomes more sophisticated and accurate.

Propagation Models

Propagation models can become quite complex if attenuations and enhancements are considered. What is presented here is a simple model of noise sources traveling in straight lines at constant speed with nothing to attenuate the noise between the source and the receiver. Noise reflections can be handled by using imaging techniques. Attenuations can be handled numerically in a conceptually simple manner; however, the computations can become quite lengthy.

The propagation model is used to determine a total energy in terms of watt seconds per square meter that will be received at a point where the noise travels in a straight line from a noise source past the receiver at a constant rate of speed. The model can be used for the infinite case where the noise source comes from negative infinity, passes the receiver at a given distance, and continues on to positive infinity. It is also possible to break up this infinitely long line into segments by using the included angle. The included angle is the angle between the lines from the receiver to the beginning point of the element under study and the ending point of the same element. This angle is in radians. If the acoustical wattage of the vehicle, its speed, and the shortest distance between the receiver and

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the vehicle's path is known, the equivalent watt seconds for its passage can be calculated by using equation (14). Appendix A contains a development of this equation.

$$I_{sec} = \frac{E_s N\phi}{4\pi dV} \tag{14}$$

where

I_{sec} = intensity seconds (equivalent watts per square meter)

E_s = power of source (equivalent watts)

d = shortest distance from receptor to the infinite line along which the source is moving (meters)

V = source velocity (meters/sec)

N = number of identical sources

ϕ = included angle (radians)

Equation (14) can be converted to feet and miles per hour to become equation (15):

$$I_{sec} = \frac{0.584\ E_s N\phi}{dV} \tag{15}$$

For the infinite case, $\phi = \pi$ and so:

$$I_{sec} = \frac{1.835\ E_s N}{dV} \tag{16}$$

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Example

Assume for this example that there is only one lane of traffic. It is located 100 feet from the receiver. It has 1,000 automobiles and 100 trucks per hour. The trucks produce 86 dBA's at 50 feet or 1.16 equivalent watts. The automobiles produce 70 dBA at 50 feet or 0.03 watts. An infinitely long highway, a background noise level of 50 dBA (0.10 micro watts per square meter), and an average speed of 55 miles per hour are also assumed. The intensity seconds due to the 100 trucks and 1000 cars can be found using equation (16).

$$I_{sec} \text{ for cars} = \frac{1.835(0.03)1000}{100(55)} = 0.010009$$

$$I_{sec} \text{ for trucks} = \frac{1.835(1.16)100}{100(55)} = 0.038702$$

The intensity seconds for the background is the average intensity multiplied by the time in seconds or;

$$I_{sec} \text{ background} = 0.1\ (10^{-6})\ 3600 = 0.000360$$

so

$$I_{sec} \text{ total} = 0.049071$$

The L_{eq} can be obtained by first dividing the total by the number of seconds to get average intensity and then using equation (9) to convert to a level:

$$L_{eq} = 120 + 10 \text{ Log}_{10}(I_{sec}/3600)$$

$$= 71.3 \text{ dBA}$$

These computations may appear involved at first glance but they can be easily simplified and they lend themselves well to computer solution.

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NOISE EMISSION MODELING

Existing Models

Commonly used noise emission models use average vehicle emission levels based on speed. These are normally integrated into the dispersion model and then the combined model is adjusted to fit field data. The resulting method is adequate to predict near term conditions and even make reasonable projections of future noise levels assuming no major change in vehicle noise emission characteristics. However, questions are now being asked that cannot be answered by this type of modeling:

Question 1.

California has legislation on the books that puts a limit on the noise emission of new vehicles. The acceptable level is set at lower and lower levels in future years. The method of acceptance testing is the SAE acceleration test.

How much benefit will result from the enforcement of this legislation?

Answer

There is no direct way of telling. The average passenger car traveling at highway speeds gives more noise from its tires than its power plant. The acceleration tests measure mostly the engine component. If the engine noise is completely eliminated, highway vehicle emissions may not be lowered by more than two or three dBA.

In any case, the existing emission modeling is not adequate to answer the question.

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Question 2.

If the current approaches are going to have such little benefit, what can be done to reduce highway vehicle noise emissions?

Answer

Here again, a quantitative answer to this question is hard to find. Current opinion is that it is time to start considering tire noise and develop schemes for the gradual introduction of quiet tires in conjunction with increased but reasonable controls on power plant emissions.

Again, existing emission modeling is not adequate to answer this question.

Model Parameters

If the idea is accepted that more sophisticated emission models are needed, the next step is to determine the parameters to which these models should be sensitive. The parameters should include not only the physical parameters that govern emissions, but also, if possible, emission components for which specific groups have some control. The physical parameters that appear to be of major concern are speed, acceleration, vehicle weight and roadway surface. The emission components are either power oriented or components which cause noise while coasting. Although this power-on/power-off division cannot be made with absolute precision, it is a workable division for solving today's problems.

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Power plant emissions are a function of speed, acceleration and the individual vehicle configuration. These emissions can best be controlled by the vehicle manufacturer backed by an adequate maintenance program and reasonable driving habits.

Coasting emissions are largely generated by the tires which are sensitive to speed, vehicle weight, roadway surface and tire design. These emissions can best be controlled by the tire industry, the highway department and reasonable driving habits. To a lesser extent, the auto manufacturers have some control because vehicle weight is a factor and undoubtedly, some coasting emissions are affected directly or indirectly by vehicle design.

Emissions Testing

A pilot study was conducted to check existing automotive noise emission factors. Five vehicles were driven by and coasted by a microphone at various speeds and their levels recorded. Vehicle idles were also measured. The power-on drive by was done at zero acceleration. The power plant noise was inferred by subtracting coast-by energy from the cruise-by energy.

Coast-by

It was found that some of the vehicles were significantly louder than others but they all showed a marked increase in noise level with vehicle speed. The tests were run at 15, 35, 55, and 75 miles per hour. The 15 miles per hour test proved inconclusive because the measured levels were too close to the background noise at the test site.

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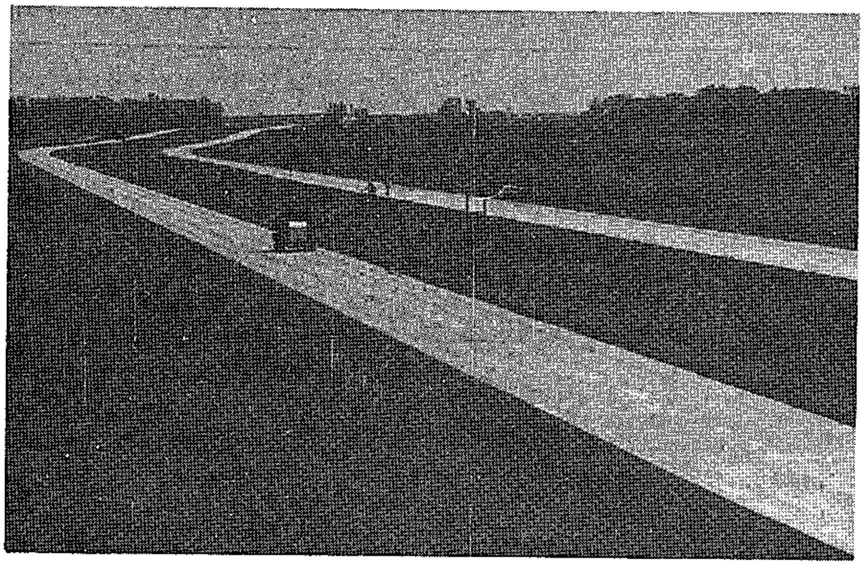
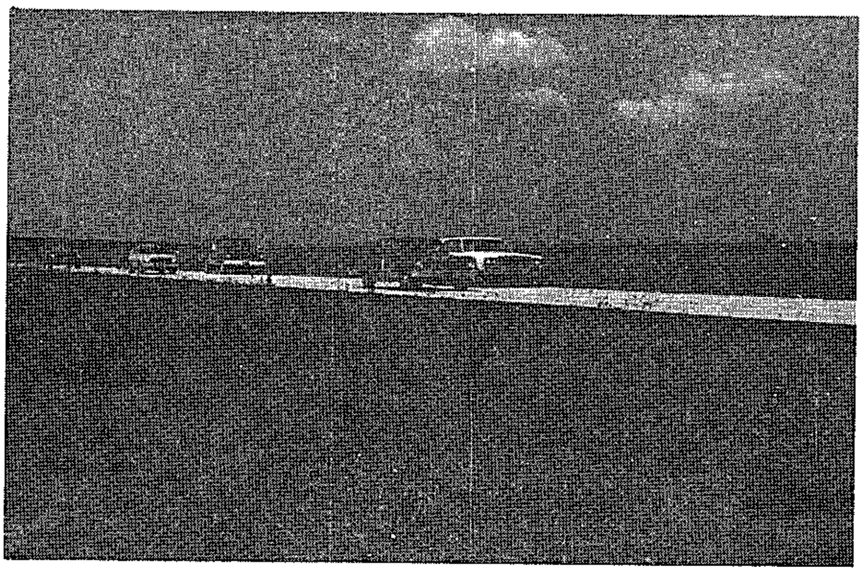
FIGURE 1



TEST SITE

Unopened section of freeway south of Sacramento.



Test vehicles making speedometer correlation run.

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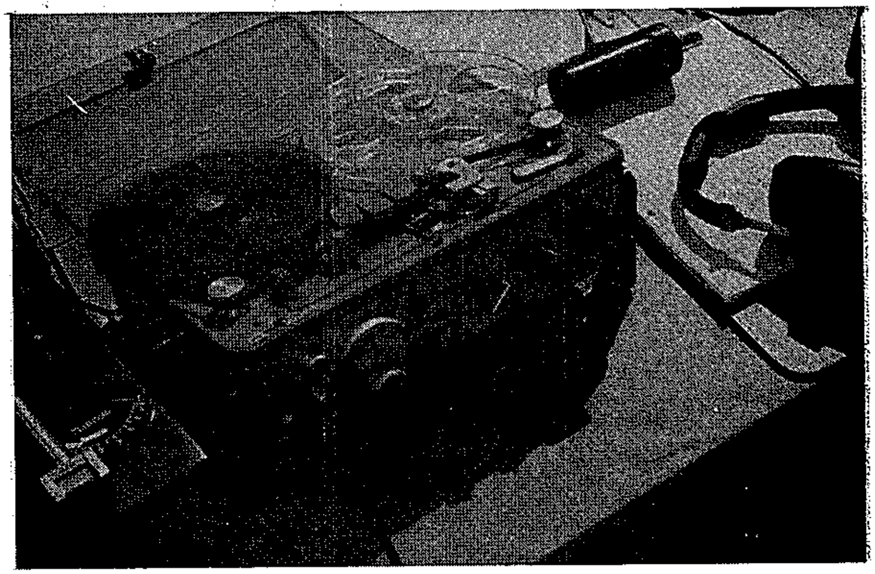
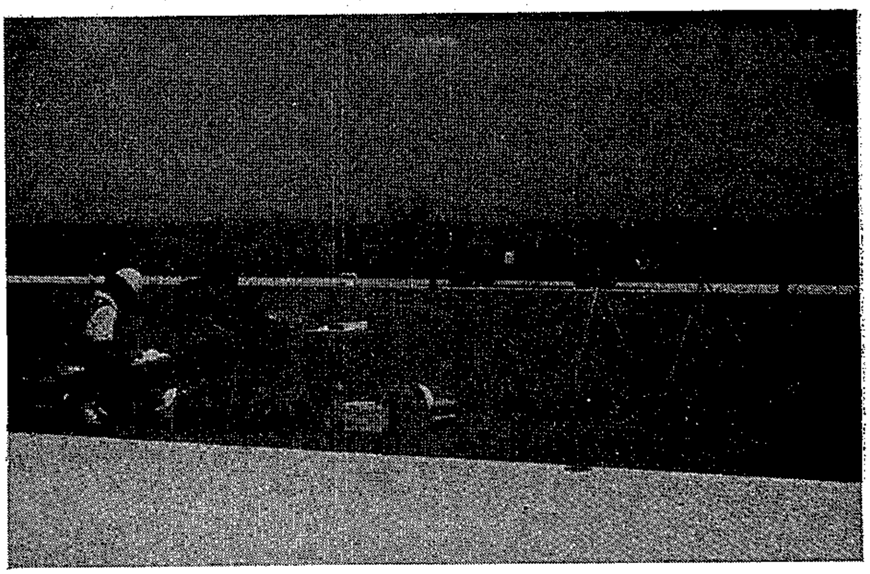
FIGURE 2



Data were recorded on magnetic tape for later analysis in the laboratory.



Test vehicle making drive-by.

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The best straight line fit of the data from 35 to 75 miles per hour was obtained by using log transforms on the speed.

Because some vehicles were markedly noisier than others, the data were normalized by subtracting the mean level at 55 mph for each individual vehicle from all the data for that vehicle. This allowed the study of the speed level relationship without the confusion of the variance due to more or less noisy tires. Figure 3 is a plot of the normalized data. A regression equation was developed:

$$L_c = L_{c55} - 58.15 + 33.55 \text{ Log}_{10} V \qquad (17)$$

where

L_c = noise level from coast-by (dBA)

L_{c55} = coast-by level at 55 miles per hour (dBA)

V = velocity of coast-by (mph)

The coefficient of correlation was 0.9827 and the 95% confidence limits on the slope were between 32.28 and 34.82.

This equation can be reduced to:

$$L_c = L_{c55} + \text{Log}_{10} \left(\frac{V}{54.1}\right)^{3.36}$$

The 95% confidence limit on the divisor for V are 46 and 62 miles per hour. Little error would be incurred by using a more logical divisor of 55 rather than the 54.1 which was developed by the regression:

$$L_c = L_{c55} + \text{Log}_{10}\left[\left(\frac{V}{55}\right)^{3.36}\right] \qquad (18)$$

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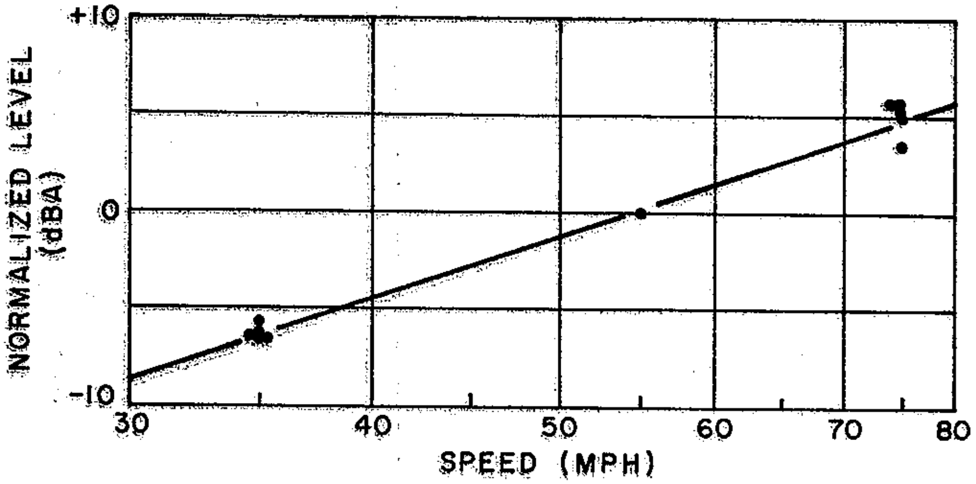
$$L_{COAST} = L_{c55} - 58.15 + 33.55 \ \text{Log}_{10} V \ (\text{dBA})$$

WHERE: L_{COAST} = LEVEL FOR COASTING (dBA)

L_{c55} = LEVEL FOR COASTING AT 55 MPH (dBA)

V = SPEED (MPH)



MEAN COAST-BY LEVELS
NORMALIZED TO MEAN LEVEL AT 55 MPH

FIGURE 3

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The 95% confidence limits on the slope, however, were 3.23 and 3.48. Although these data are limited and these tests have not been replicated, it appears the tire noise is a function of something more than the cube of speed.

In energy terms, equation (18) becomes:

$$I_c = \left(\frac{V}{55}\right)^{3.36} \text{Antilog} \left[\frac{L_{c55}}{10} - 12\right] \qquad (19)$$

where

I_c = energy intensities of coast-by in equivalent watts per square meter as measured at 50 feet.

Power Plant Emissions

The amount of noise generated by the power plant was inferred by subtracting the energy equivalent of the mean coast-by level from the energy equivalent of the mean drive-by for each vehicle at each speed. The idle level was used as zero miles per hour. These levels were plotted against speed as shown on Figure 4. Although some vehicles appear to be louder than others, there was no consistency in this so it was decided not to try to normalize these data. A regression equation was calculated and the following equation developed:

$$L_p = 48.5 + 0.29\ V \qquad (20)$$

where

L_p = level of power plant emissions (dBA)

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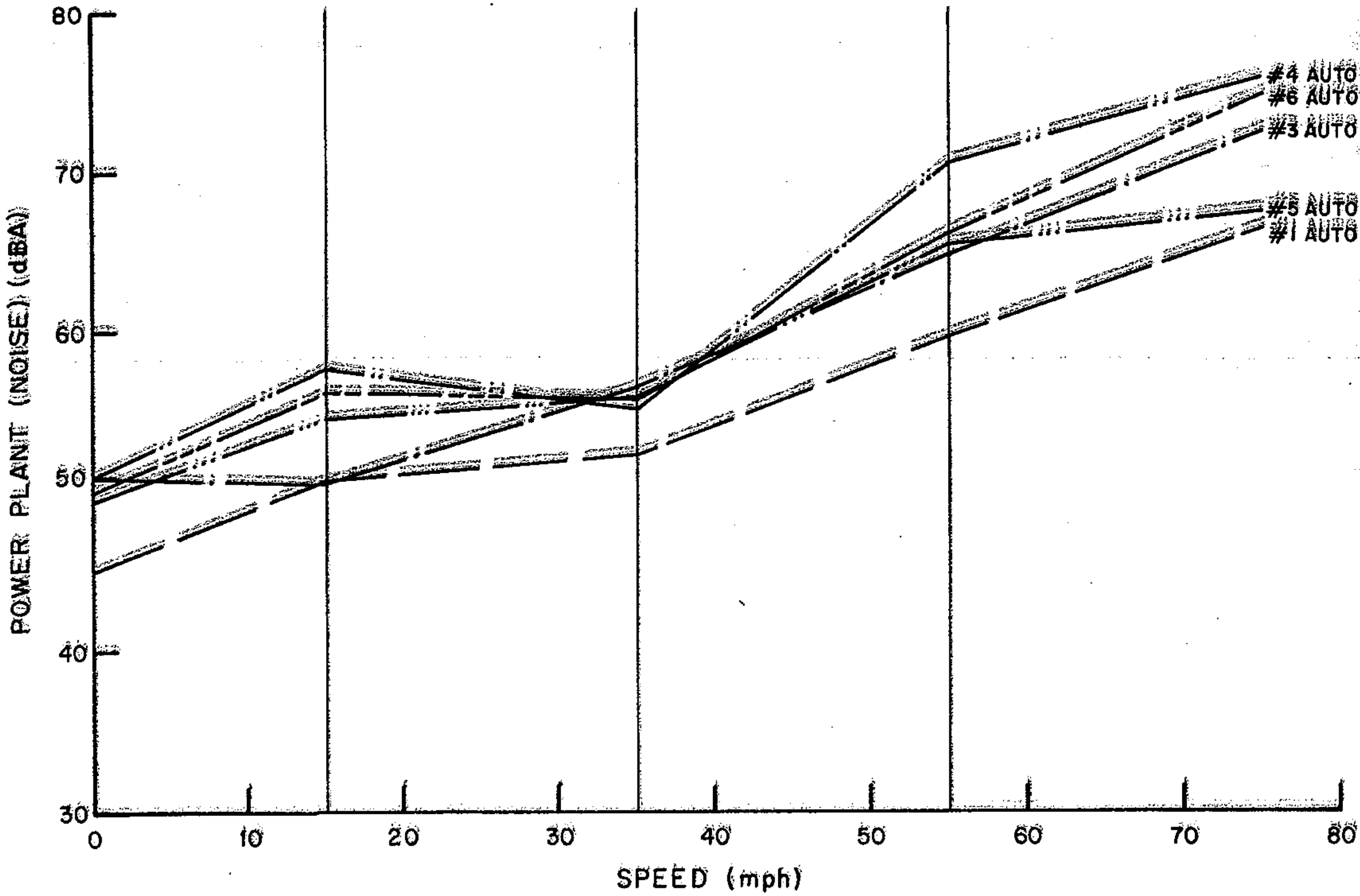

SPEED VS POWER PLANT

FIGURE 4

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The coefficient of correlation was 0.92 and the 95% confidence limits on the intercept were between 46 and 51 dBA and the slope was between 0.24 and 0.35; however, the calculations involved working with means so the actual variances will be significantly larger than the calculations indicate. In energy terms, equation (20) becomes:

$$I_p = \text{Antilog } (0.029V-7.15) \qquad (21)$$

where

I_p = energy intensity of power plant in equivalent watts per square meter as measured at 50 feet.

Combining Emission Equations

The two energy equations can be combined to give an empirical equation that fits our test data from zero to 75 miles per hour. The energy intensities can be calculated separately for cruise and power plant emissions, added together and then converted to dBA, using equation (5).

If the entire operation to be performed by one equation, the following can be used:

$$L = 10 \text{ Log}_{10}\left[\left(\frac{V}{55}\right)^{3.36} \text{Antilog}\left(\frac{L_{c55}}{10}\right) + \text{Antilog}(4.85+0.029V)\right] \qquad (22)$$

where

L = maximum sound level from vehicle pass-by at 50 feet (dBA)

V = vehicle velocity (mph)

L_{c55} = maximum sound level from vehicle coast-by at 50 feet and 55 mph (dBA).

Figure 5 is a plot of the resulting curves. The mean of cruise-by test data is also shown.

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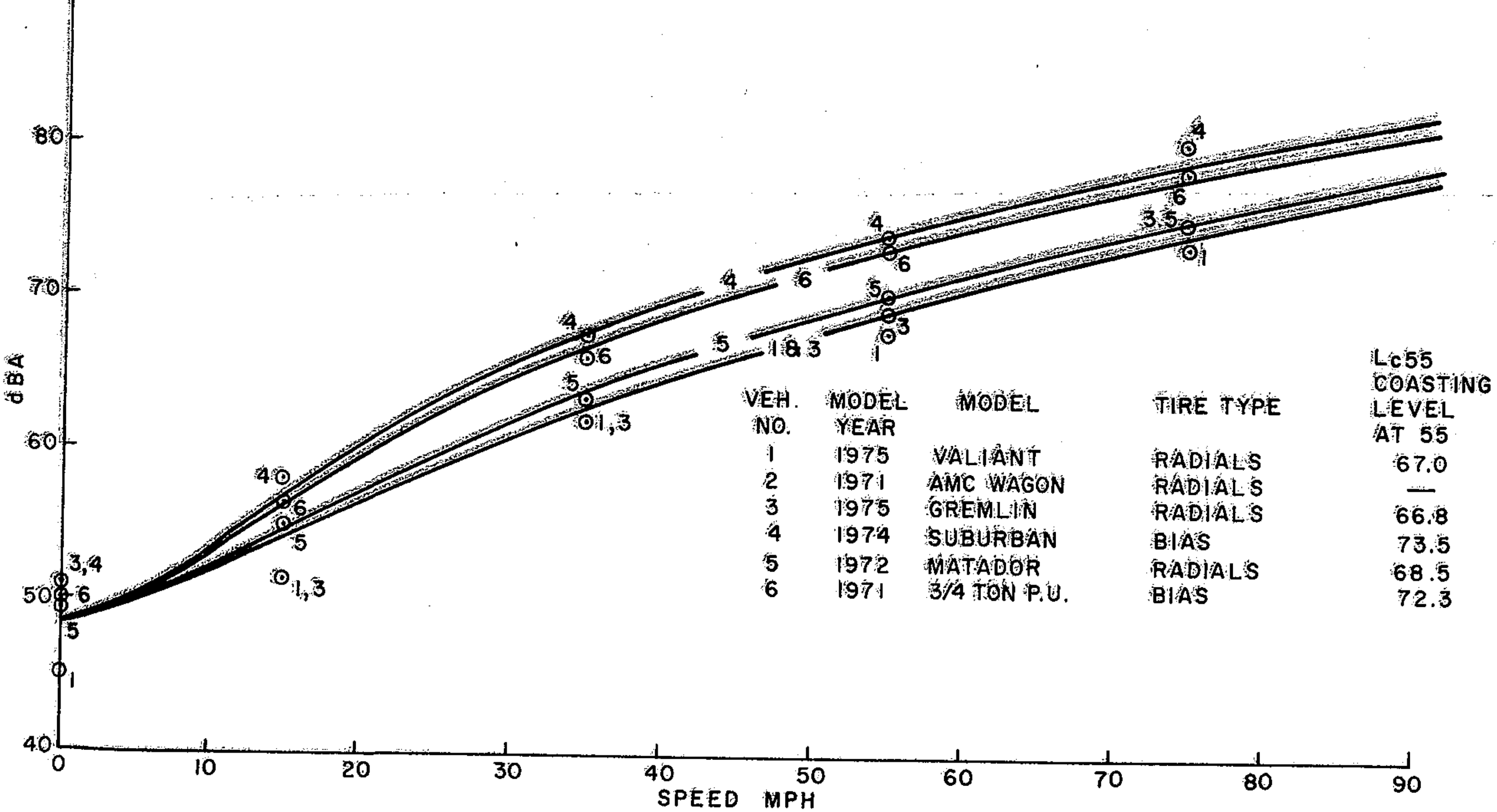
CALCULATED EMISSION LEVELS IN dBA VS SPEED IN MPH

$$L = 10 \log_{10}\left[\left(\frac{V}{55}\right)^{3.36} 10^{\left(\frac{L_{c55}}{10}\right)} + 10^{(4.95+0.029V)}\right]$$

WHERE : L = LEVEL AT CRUISE

L_{c55} = LEVEL AT COAST AT 55 MPH

⊙ MEANS OF OBSERVED CRUISE-BY'S



VEH. NO.	MODEL YEAR	MODEL	TIRE TYPE	Lc55 COASTING LEVEL AT 55
1	1975	VALIANT	RADIALS	67.0
2	1971	AMC WAGON	RADIALS	—
3	1975	GREMLIN	RADIALS	66.8
4	1974	SUBURBAN	BIAS	73.5
5	1972	MATADOR	RADIALS	68.5
6	1971	3/4 TON P.U.	BIAS	72.3

FIGURE 5

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NOISE BARRIERS

Noise Diffraction Calculations

The effectiveness of an adequately long barrier is limited by the diffraction of noise over it. Two methods of making this calculation were studied and a method was selected. The calculations are frequency sensitive and traffic noise is composed of a wide range of frequencies so it was necessary to develop a traffic noise source model composed of eight incremental sources of different frequencies. A computer program was written to do the necessary diffraction calculations and a nomograph was later developed as a rapid graphical approximation.

Selections of a Predictive Method

Methods of predicting the diffraction of noise over barriers have been presented in the literature by Maekawa (6) and Rettinger (5). Maekawa's method was empirically derived and is somewhat limited in its use. Rettinger's method employs more rigorous mathematics, but is complex. Both of these methods are good only for single frequencies.

Computer programs were written to solve the diffraction problem using both Maekawa's and Rettinger's methods. Existing barriers were then studied, and the collected field data were compared with the calculated results from both methods. The calculations using Rettinger's method correlated as well or better with field data than did calculations based on Maekawa's method. Because a computer was available, the complexity of Rettinger's method was not considered a major hindrance, and Maekawa's method is limited to those cases where the barrier is closer to the source than to the receiver. The investigators also prefer to work with rigorous solutions as they lend themselves to extrapolation and promote greater understanding of the physical phenomena involved.

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Rettinger's equation is written:

$$SLR = -3 + 10\ \text{Log}[(0.5-S_x)^2+(0.5-C_x)^2] \tag{22}$$

where

SLR = Sound Level Reduction in decibels

S_x and C_x = Fresnel integrals of the value V as determined by:

$$V = h\left[\frac{2(a+b)}{\lambda ab}\right]^{0.5} \tag{23}$$

where

λ = wavelength in feet

a = distance from source to the barrier along a line of sight with the receiver

b = distance from the barrier to the receiver along a line of sight with the source

h = height of barrier perpendicular to a line of sight between the source and the receiver. h becomes zero when the line of sight grazes the barrier and h is negative when the line of sight passes over the barrier (feet)

V = value used to determine Fresnel integrals.

Equation (22) can be rewritten in energy terms to become:

$$I_a = I\frac{[(0.5-S_x)^2+(0.5-C_x)^2]}{2} \tag{24}$$

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where

I_a = attenuated intensity in equivalent watts per square meter

I = unattenuated intensity

S_x and C_x = Fresnel integrals of the value V given in equation 23.

The computation of the Fresnel integrals can be expensive but cheaper approximation methods can undoubtedly be developed.

Point Source Prediction

These studies were limited to the effect of a barrier on peak noise generated by a single vehicle pass-by. The peak is normally reached when the vehicle is closest to the receiver so a calculation at a single vehicle location would suffice to calculate the barrier effectiveness.

This is not the case in L_{eq} modeling; however, where each noise source must be considered from the time it first comes into hearing until it fades again into the background. The geometrics of the problem are continually changing during that time. As a result, rigorous calculation of the total effect of the barrier can be a very complex proposition. The first step, however, is to develop the peak noise attenuation calculations. Once a peak noise reduction method is established, it is a conceptually simple task to use numerical analysis techniques to develop methods for use in L_{eq} modeling.

Two types of attenuation are normally considered in point source barrier modeling. The distance attenuation is 6 decibels per doubling of distance. The "excess" attenuation afforded by the barrier is then calculated and combined with the distance attenuation to predict the intensity of sound reaching the receiver.

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Because of the frequency sensitivity of barriers, the noise source is considered to be composed of 8 incremental noise sources located at the same point but of different frequencies. (The development of this model is discussed in Appendix D). The energy intensity at the receiver from each of the incremental sources is calculated, the results summed and then converted to decibels to give the predicted level.

Practical Considerations of Noise Barriers

Noise barriers can be made of virtually any material that is air tight and reasonably massive as long as it is adequately long and well sealed. A rule of thumb is that noise barrier material should weigh more than 4 pounds per square foot. If the barrier material satisfies these requirements, the limiting factor on its performance will undoubtedly be the diffraction of noise over it or noise flanking it. Barrier materials that absorb sound on the highway side reduce noise reflections back to the highway and beyond but give little or no additional protection to receivers behind the barriers. Absorptive material on the receivers side of the barrier may help reduce reverberations between buildings and the barrier. Absorptive barriers will probably be expensive, hard to clean and maintain, and less resistive to weathering.

A primary consideration of barrier design is durability. Barriers must be able to resist heavy wind loading, weathering, vandalism, etc., with little or no maintenance. A design wind load of 20 lbs. per square foot has been suggested for barriers located where failure would not be catastrophic. Sound barriers which are to be placed on bridges, retaining walls, or other critical locations should receive special consideration.

If barriers are located close to the traveled way, the designer must consider what would happen if a vehicle struck the barrier. Barriers close to the traveled way should be mounted on, or protected by, traffic barriers.

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Noise barriers could have adverse visual effects. They may reduce sight distances or be aesthetically unpleasing. Imaginative design should reduce these problems.

There are places where noise barriers will not be practical for geometric reasons. Some interchanges may be very difficult to screen. It may be difficult to build practical noise barriers in some hilly terrain. It is sometimes impossible to screen residences located on hillsides overlooking a freeway. On the other hand, imaginative use of highway geometrics may reduce or even eliminate the need for barriers in many locations. Barriers may or may not be costly items. In certain instances earth-mounding can be used to good effect at very little cost. At other times, low barriers may be built at reasonable cost, although $30 per running foot appears to be a minimum in recent CALTRANS contracts.

In other cases, addition of noise screening may require extensive revision of the drainage system, purchase of additional rights of way and costly additional construction. High barriers are usually expensive and cost upwards of $50 a foot. Many have cost $100 per foot or more. Noise barriers located close to traffic will require traffic barrier type bases. Elevated structures already have traffic barriers. Extending these barriers up a few feet may not be prohibitively expensive.

Many of the barriers built to date have been made from concrete block. These can be made aesthetically pleasing. Reinforced concrete is a practical barrier material, and various types of panels have been used.

Maintenance and Emergency Access

One consideration that is often overlooked when designing a barrier is the need for access through the barrier for highway maintenance and public safety purposes. A paper study was

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performed to determine how these openings could be provided without deteriorating the effectiveness of the barrier. The only practical solution found is to use doors or some other type of moveable panel.

These doors can be hidden between overlapping panels. The use of baffles alone will reduce the effectiveness of the barriers. Doors should be six feet wide for maintenance access and probably as wide for emergency access. Personnel using these openings will be burdened with equipment, trash, tools, etc., so adequate consideration should be given to their safety and convenience. This is particularly true if there is a differential in grade across the barrier.

EXISTING NOISE BARRIERS

As previously mentioned, some noise barriers are currently in operation along California highways. Two earth berms have been studied and they are discussed below. In addition, a concrete block/berm combination has been reported (2). Additional barriers of concrete block, precast panel, steel and stucco have been built but have not yet been adequately evaluated for inclusion in this report.

Low Earth Berm

A field study was made of a low berm in front of an apartment building on Folsom Boulevard in Sacramento, California.

The apartment manager stated that the berm had been placed as a noise attenuating device to protect a lawn and swimming pool area in front of the building.

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Attenuations were calculated using Rettinger's equation and composite truck noise models. These noise models were composed of a series of point sources located as shown on Figure 6. The point source at 5 feet above the pavement represents engine noise. The 10 foot noise source simulates truck exhaust noise. The sources below pavement grade are used to simulate reflfections off the pavement or sidewalk. As can be seen in the table, the calculated attenuations corresponded quite closely with the measured attenuations.

This same approach was attempted with the autos but the measured attenuations were much less than what was calculated. This discrepancy was at least partially due to several factors:

1) The assumed auto noise source was at pavement grade.

Significant noise may be radiating from relatively higher up on the measured cars.

2) The background noise levels were high enough to affect the measurements. An undoubtedly important contaminant was noise from some other autos which arrived along paths that flanked the berm.

3) There may have been significant reflections from objects and buildings in the area.

In our opinion, the high background noise levels were the main cause of the discrepancy. Background noise and flanking noise are a major problem in measuring barrier effectiveness.

<u>Eleven Foot Earth Berm</u>

An eleven foot high earth berm has been constructed to protect the hardstand area of a drive-in church from traffic noise maxima.

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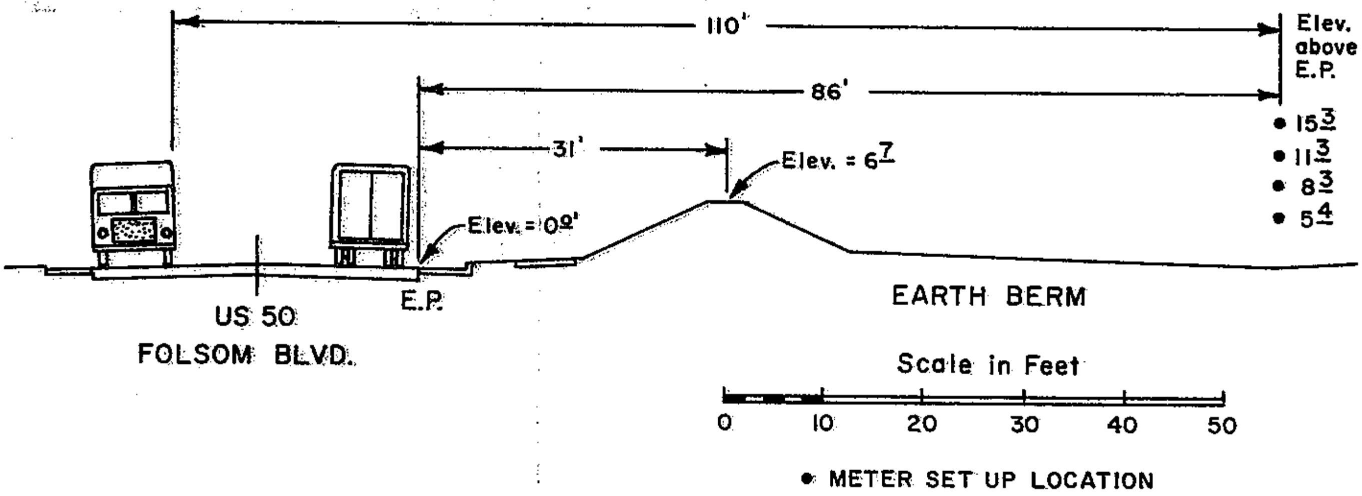
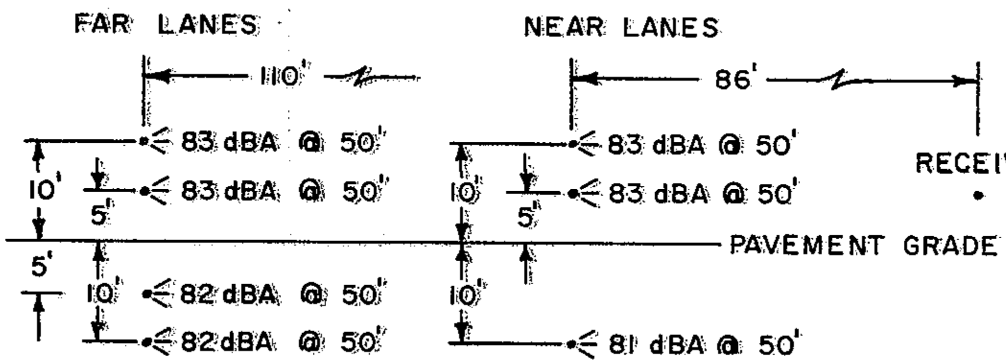


DISTANCE FROM SOURCE	ELEV. ABOVE E.P.	EXCESS ATTENUATIONS BEHIND BERM CALCULATED	MEASURED
86'	5.4'	5.6dB	4.2dB
86'	8.3'	3.9	4.7
86'	11.3'	2.8	3.9
86'	15.3'	1.6	1.8
110'	5.4'	8.0	7.8
110'	8.3'	5.5	5.9
110'	11.3'	3.6	5.0
110'	15.3'	2.2	3.7

TRUCK NOISE MODELS USED



BELOW GRADE SOURCES SIMULATE REFLECTIONS

FIGURE 6

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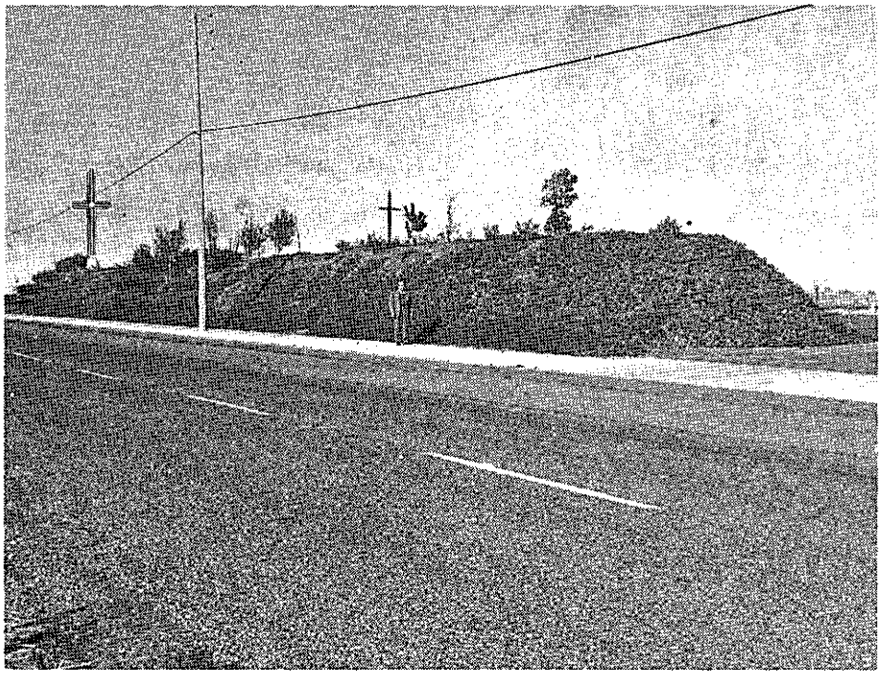
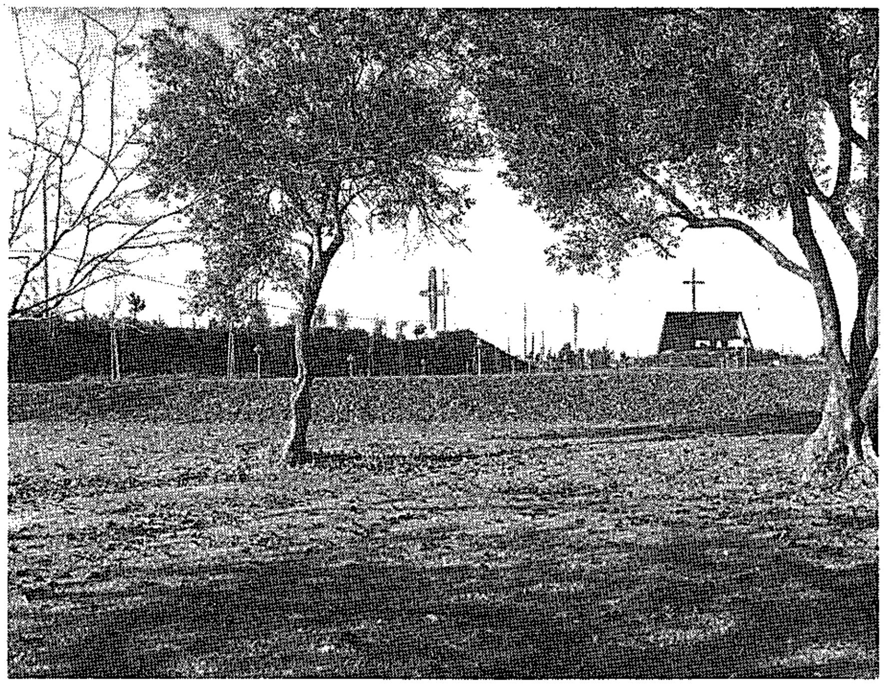
FIGURE 7





Drive-in church located south of
Sacramento on U.S. 99.

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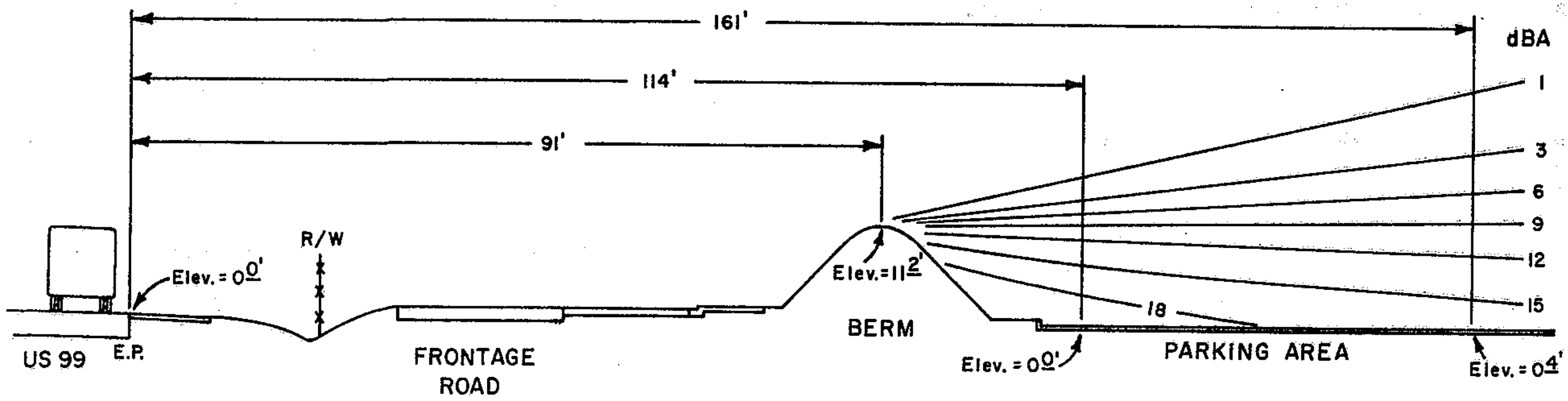
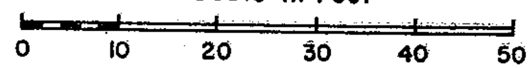


DISTANCE FROM E.P.	ELEVATION ABOVE E.P.	NOISE LEVELS CALC.	NOISE LEVELS MEAS.	ATTENUATIONS CALC.	ATTENUATIONS MEAS.
114.0'	5.0'	64.5	65.3	16.5	15.2
114.0'	8.0'	67.5	65.5	13.5	12.9
114.0'	12.0'	73.2	73.4	7.8	6.8
114.0'	15.0'	78.1	76.2	2.9	3.3
161.0'	5.0'	64.0	64.0	14.0	12.8
161.0'	8.0'	65.8	64.8	12.2	10.5
161.0'	12.0"	68.7	71.9	9.3	6.1
161.0'	15.0'	71.2	71.0	6.8	5.3



TRUCK NOISE

EXCESS ATTENUATION BEHIND AN EARTH BERM

FIGURE 8

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The church is located south of Sacramento on U.S. 99. Figure 7 is two pictures of the berm and church. The church fronts on a frontage road and the berm is located about 90 feet from the freeway edge of pavement.

Measurements were made at various distances and elevations behind the berm. The same test method was used as previously described. One meter was placed on top of the berm and the other was located at various places behind it. Gross attenuations were measured. The distance attenuation was calculated and subtracted. The resultant was the net or "excess" attenuation of the berm.

The noise levels and excess attenuations were also calculated. The noise model consisted of four sources. Two were located at 5 and 10 feet respectively, above the pavement to simulate engine and exhaust sources. Two were located below grade to simulate reflections.

The calculations correlated very closely with experimental results and are believed to be close to or within the experimental error. Figure 8 shows a cross section of the church berm. Plotted on the cross section are curves representing calculated excess attenuations behind the berm. The table gives actual and calculated values for the points measured in the field.

RECOMMENDATIONS FOR FUTURE WORK

There are several areas in critical need of additional study. A method should be developed to monitor vehicle emissions on existing facilities so that emission models can be developed, checked, updated and generally calibrated to a given locality. The tire roadway interaction should be studied so that the

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designer can make more positive use of his pavement design and pavement maintenance options. Tire/pavement information is also basic to the development of quieter tires.

Another area requiring major effort is the rigorous development of ground and barrier attenuation prediction methodology. Unless a rigorous knowledge of this phenomenon is developed, the designer will be restricted to the use of field proven designs when cheaper, more effective and more aesthetic solutions may be available.

Monitoring Vehicle Noise Emissions

The vehicle emission study should be conducted on existing highways by monitoring existing traffic flow and measuring the resulting noise. The execution of this study, however, may not be a simple task; it will require methodology to not only count the vehicles, but also to get vehicle type and speed. In addition, it may be necessary to monitor over an extended period of time to obtain adequate sample sizes.

A monitoring system should be simple and portable and require little or no installation costs. It should be easily usable on existing highways on a routine basis to monitor the noise emissions of the vehicles using that facility. This would allow calibration of noise design methods and evaluations of vehicle noise reduction programs.

Diffraction, Absorption, and Scattering

The rigorous study of barrier diffraction, ground absorption and noise scattering effects will require a broad area of expertise. The study must be predicated on a thorough mathematical understanding of the physics involved. Calculations must be checked, however, by measurements on existing highways and/or by model studies. It is not envisaged that this study

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will soon be completed. The initial research will be aimed at the general case. Later research would delve into special cases and "clever" new approaches to generalized or specific problems.

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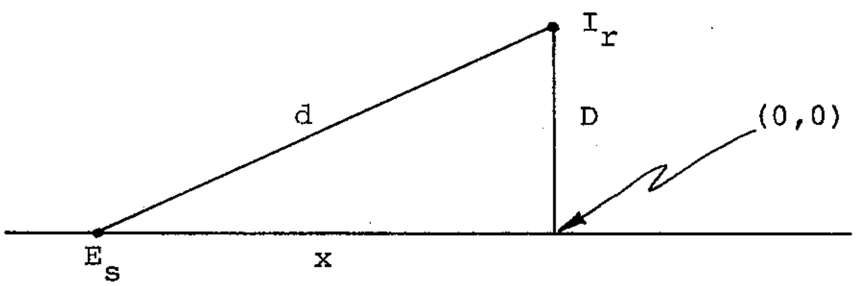
APPENDIX A

Development of an L_{eq}

Noise Transmission Model

This model is used to determine the total energy in terms of equivalent watt seconds that is received from a constant and omnidirectional noise source traveling along a straight line at a constant rate of speed. Figure A1 illustrates the problem setup:

FIGURE A1



Where:

I_r = energy intensity at the receiver as received from the source (equivalent watts/m^2).

E_s = energy of source (equivalent watts). The source in traveling along the x axis.

d = instantaneous distance from the source to the receiver (m).

D = perpendicular distance from the line of travel to the receiver (m). The origin is the nearest point on the x axis to the receiver.

x = instantaneous location of the source along its line of travel which is the X axis.

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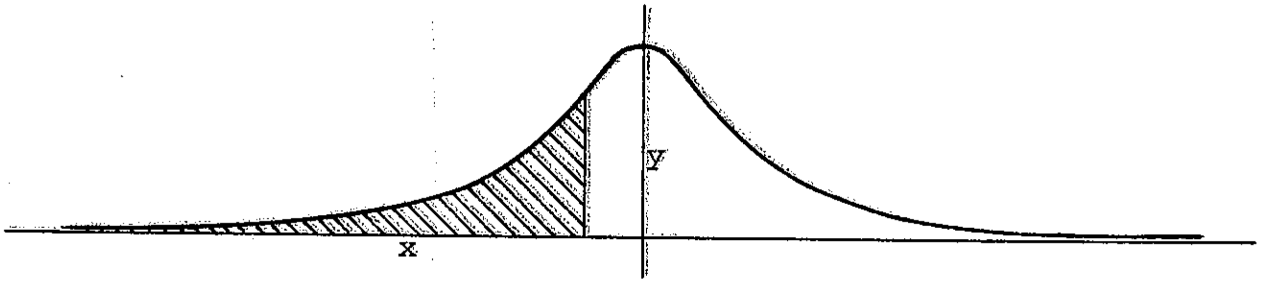
Figure A2 illustrates the curve under which the area is to be determined.

FIGURE 2



Where:

$y = I_r$ for respective locations on the x axis.

x = the instantaneous location of the moving source.

The area under the curve between any two values of x give the intensity integrated over distance. If it is assumed that the source is traveling at a uniform speed then the distance can be expressed in terms of time and the area under the curve can be expressed in terms of energy intensity times time:

$$I_r = \frac{E_s}{4\pi d^2}$$

The theory of Pythagoras states:

$$d^2 = x^2 + D^2$$

so

$$I_r = \frac{E_s}{4\pi(x^2+D^2)} \qquad \text{(A1)}$$

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and the area under the curve can be expressed as:

$$I_d = \int_{x_1}^{x_2} I_r \, dx \qquad \text{(A2)}$$

where

I_d = summarized energy intensity at the receiver (watt m/m^2).

Substituting A1 for I_r:

$$I_d = \int_{x_1}^{x_2} \frac{E_s}{4\pi(x^2+D^2)} \, dx \qquad \text{(A3)}$$

Integrating:

$$I_d = \frac{\frac{E_s}{4\pi D}\Big|_{x_1}^{x_2} \tan^{-1}\frac{x}{D}}{x_2 - x_1} \qquad \text{(A5)}$$

The tangent term becomes the included angle (phi) between the receiver and any two values of x so:

$$I_d = \frac{\frac{E_s\phi}{4\pi D}}{\Delta x} \quad \left(\frac{\text{watt m}}{\text{m}^2}\right) \qquad \text{(A5)}$$

Speed is now incorporated to convert the area from intensity times distance to intensity times time.

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$$\frac{\Delta x}{V} = \text{time (sec)}$$

so

$$I_{sec} = \frac{I_d \ \Delta x}{V} = \frac{E_s \phi}{4\pi DV} \tag{A6}$$

where:

I_{sec} = summarized energy intensity at this receiver (watt sec/m^2).

E_s = energy of the source (watts).

ϕ = the angle subtended by the straight line element under study (radians).

D = the perpendicular distance from the infinite line including the element to the receiver (m).

V = the velocity of the source (m/sec).

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APPENDIX B

Noise Barrier Nomograph Method

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TRANSPORTATION LABORATORY

State of California
Department of Transportation
Division of Construction and Research

Method No. Calif. 702A

July 7, 1975

NOMOGRAPH METHOD FOR PREDICTING THE BENEFIT OF TRAFFIC NOISE BARRIERS

Scope

A nomograph solution to estimating the effectiveness of noise barriers in attenuating truck noise peaks is described in this method.

Application

This method is only for use in predicting attenuations of diesel truck noise peaks. Its principal area of application is barrier design for compliance with section 216 of the California streets and highways code which establishes 50 dBA as the peak noise limit in school classrooms. This method is not applicable to predicting attenuations of L_{10}, L_{50} or L_{eq}. Peak level attenuations are usually significantly higher than the attenuations afforded time distributed levels.

Procedure

A. Noise Model

This nomograph was developed for estimating attenuations of diesel truck peaks. A single point source located eight feet above the pavement should be used.

B. Cross Sections

A cross section should be drawn (or calculated) and should include the noise source, the noise receiver and the noise barrier. A cross section should be drawn to scale and represent the worst case path between the source and the receiver. Cross sections are normally drawn perpendicular to the traveled way but this may be modified if a less shielded path exists. A scale of 20 feet to the inch is usually adequate. Figure 1 is an example.

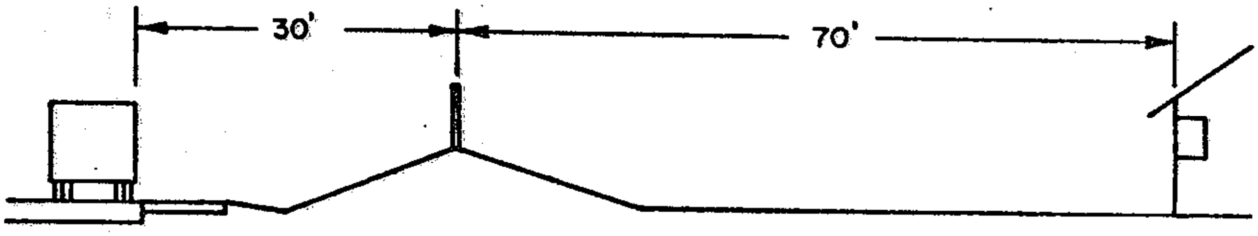

Figure I

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C. Geometrics

The user must now determine dimensions A, B, and H for use on the nomograph. Dimensions A and B are determined by measuring along a straight line between the source and the receiver (i.e. line of sight). A is the distance from the source to a point perpendicular to the top of the barrier. B is the distance from the receiver to the same point. H is the optical height of the barrier. The optical height is the perpendicular distance from the line of sight to the top of the barrier. If the line of sight passes over the top of the barrier, the optical height is negative. The optical height is zero when the noise source is just visible from the receiver. These dimensions are illustrated in Figure II.

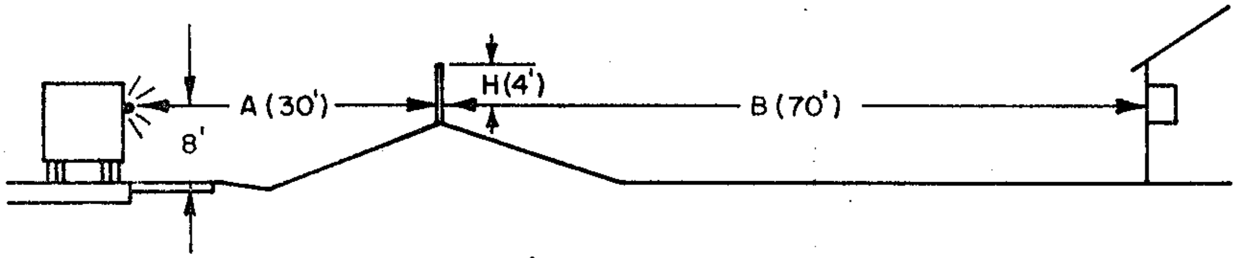

Figure II

D. Use of the Nomograph

The "Determine V/H factor" nomograph (Figure IV) is entered first. The dimensions A and B are located on their respective lines and a straight line is drawn between them. In the example (Figure II) distance A is 30 feet and distance B is 70 feet. The V/H factor is then 0.195. H is positive so the next step is to enter the "Determine Sound Level Reduction" nomograph (Figure V). The V/H factor is located on its line and the height H is located on its proper line (H>0). A straight line drawn between these points intersects the SLR line at 12. The sound level reduction of the example barrier is 12 dBA. If the line of sight between the noise source and the noise receiver had passed over the top of the barrier then H would have been negative and the H<0 line would have been used.

E. Determining expected peak sound levels

First, determine what the expected peak sound level would be if the barrier were not present. This value can be obtained from Figure III (1) which is based on the maximum legal noise emission for a heavy duty (6,000+ lb) vehicle on a California highway. Heavy trucks actually average four or more dBA lower than this. In the example, the receiver is located 100 feet from the noise source so the maximum peak noise level expected from a legal truck will be 84 dBA. The sound level reduction determined from the nomograph is subtracted from this value. The example sound level reduction was 12 dBA, so the projected maximum peak noise level will be 72 dBA at the shielded receiver.

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REFERENCE

1. Beaton, J. L., Bourget, Louis, "Traffic Noise Near Highways, Testing and Evaluation", State of California, Materials and Research Department, Research Report No. CA-HY-MR-6316-2-72-43

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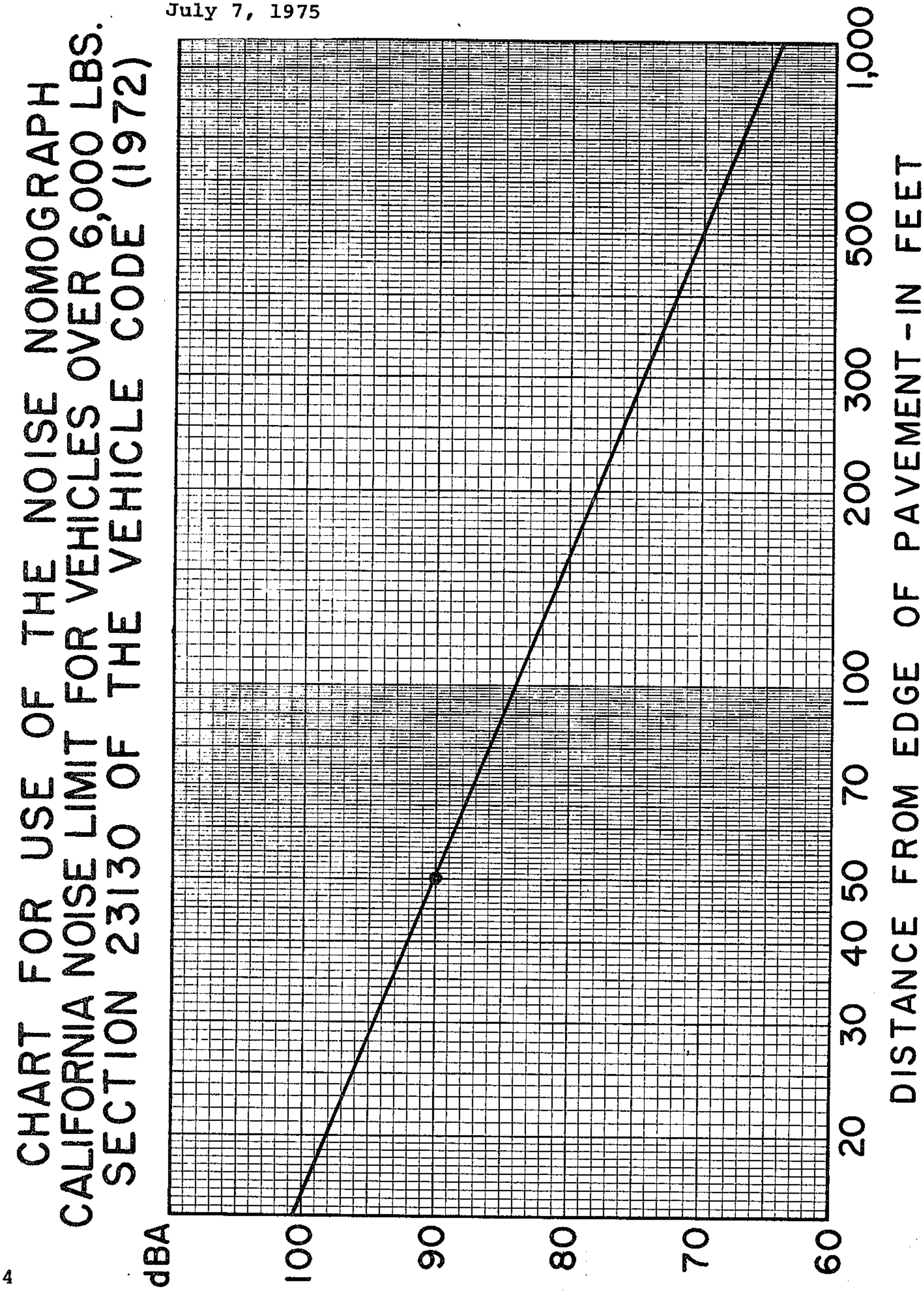

Figure III

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NOISE BARRIER ATTENUATION NOMOGRAPH

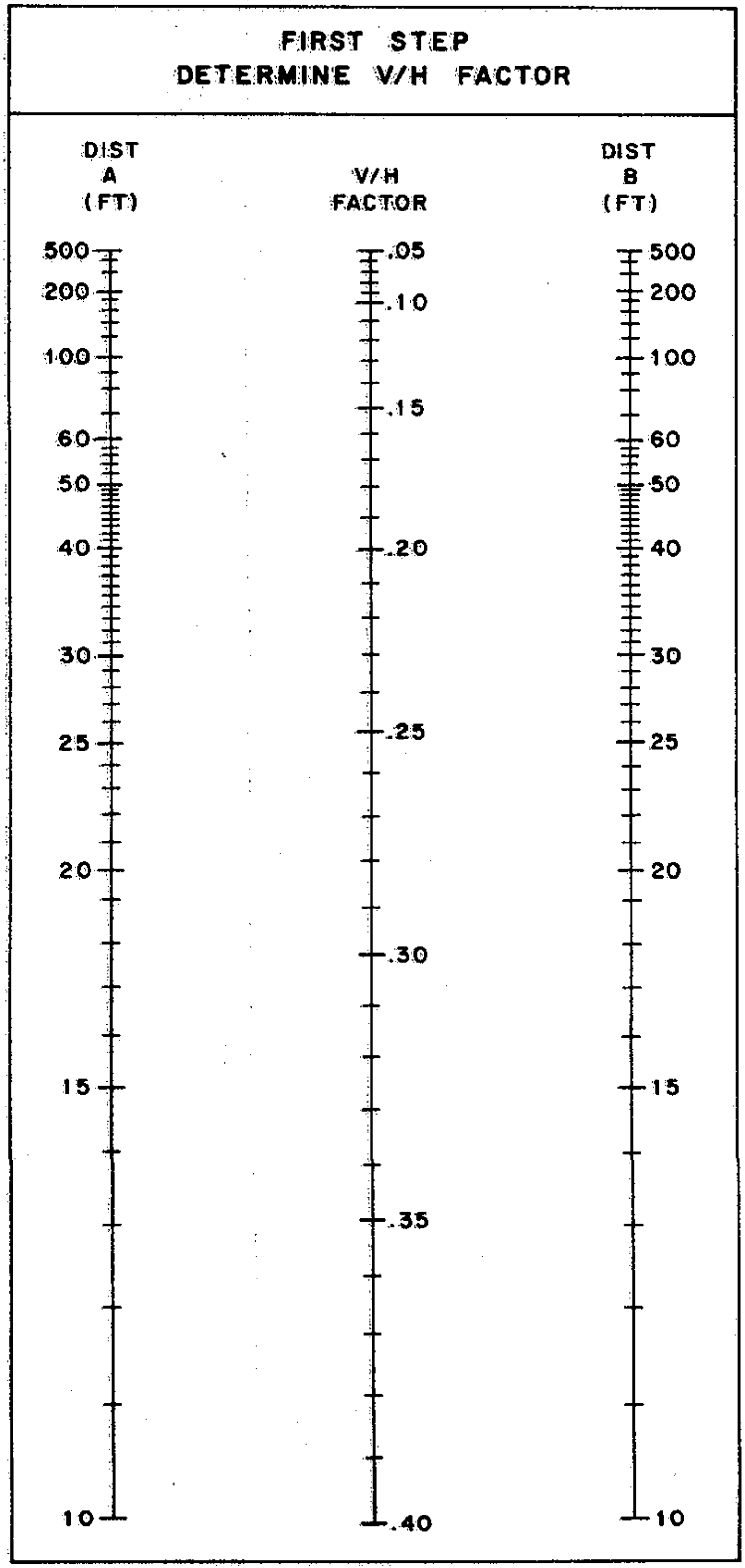

Figure IV

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NOISE BARRIER ATTENUATION NOMOGRAPH

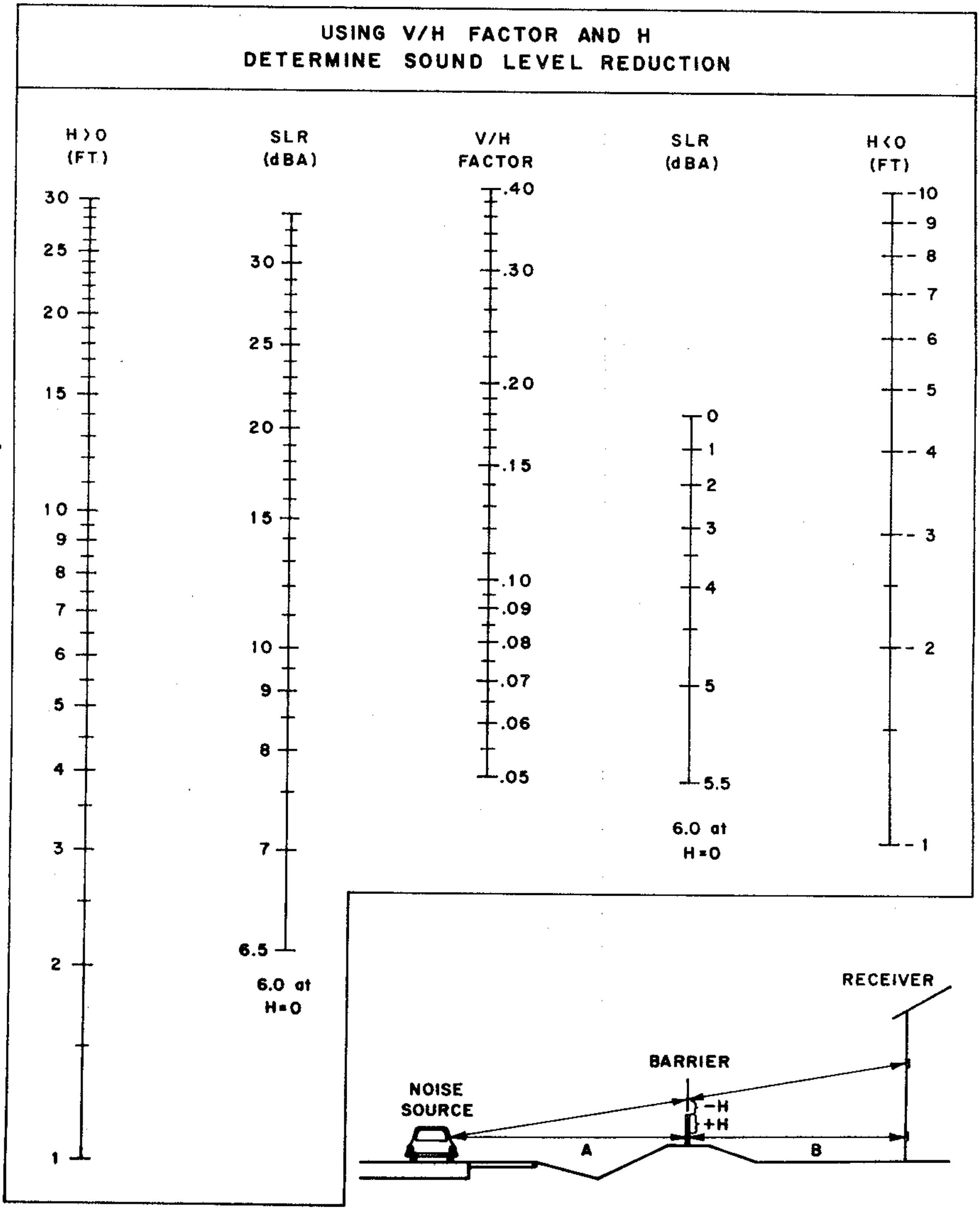

Figure V

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APPENDIX C

Noise Barrier Design Method (Computer Based)

A computer program has been written which can be used to evaluate noise barriers. It is presently available to Caltrans engineers and can be accessed on the Department's TENET Time Share Service. The relative location and noise level of the noise source(s) and the relative locations of the barrier and the receiver are input to the computer. The computer then outputs calculated noise levels with and without the barrier. The computer also prints out the sound level reduction caused by the barrier and the energy intensity in equivalent watts per square meter with and without the barrier.

The Noise Source

Diesel trucks are the loudest of the noise sources that appear in volume on California highways. Therefore, they are the basis of the noise model. The model could consist of one noise source of 86 dBA but two noise sources of 83 dBA each would also sum to the 86 dBA at 50 feet.

The effective elevations of the noise source varies from truck to truck. The major noise generators from a diesel truck are its exhaust, the exhaust stack itself, engine compartment radiations, the air intake, engine compartment/pavement reverberations, and tire and roadway interaction noises. There are also aerodynamic noises and some trucks produce loud body noises.

Bearing all of this in mind, it is suggested that a single point source noise model be used and it should be located eight feet above the pavement. A 90 dBA source strength should be used when designing for compliance with Section 216 of the California Streets and Highways Code. The user may want to use more complex noise models to account for reflections.

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Geometrics

The user must now determine the relative locations of the sources, the barrier and the receiver. There are two methods available. If a cross section has been drawn to scale, it is easy to use line of sight distances. If not, it is perhaps easier to use horizontal and vertical coordinates.

If the user decides to use the line of sight distances he must first determine the noise level of each source as measured at 50 feet. Then, measuring along a straight line between the source and the receiver, the user must determine the distance from the source to a point perpendicular to the top of the barrier, the distance from this point to the receiver, and the optical height of the barrier. The optical height is the perpendicular distance from the straight line to the top of the barrier. If the line of sight passes over the top of the barrier, the optical height is negative. The optical height is zero when the noise source is just visible from the receiver. These dimensions are illustrated on Figure I.

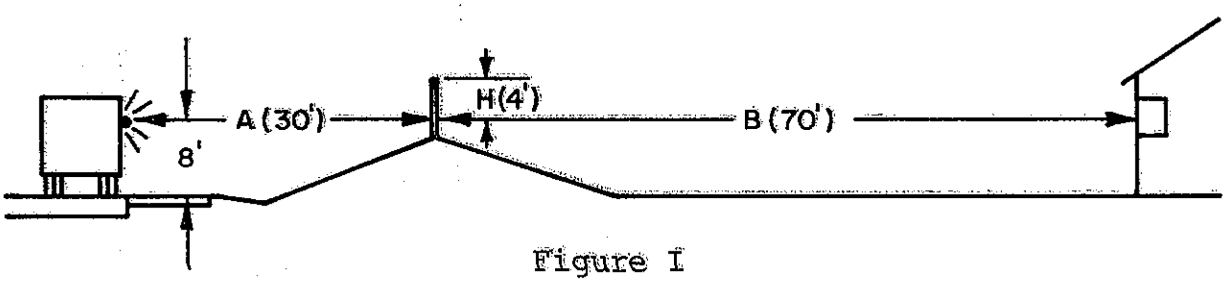

Figure I

If the user has not plotted a cross section to scale, he may prefer to use horizontal and vertical coordinates of the source, barrier and receiver.

Figure II is a copy of the example problem run using both optical height and coordinate method. User input is underlined.

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```
BASIC
>LINK '5;LAB;NOISEBAR'

 FOR CALCULATIONS USING LINE OF SIGHT DISTANCES
 AND PERPENDICULAR HEIGHTS:                   INPUT 1

 FOR CALCULATIONS USING HORIZONTAL AND VERTICAL
 COORDINATES (TWO DIMENSIONS):                   INPUT 2   ?1


 HOW MANY SOURCES   ?1

 INPUT FOR EACH SOURCE:
       NOISE LEVEL AT 50 FEET (DBA)
       SOURCE TO BARRIER DISTANCE (FT)
       BARRIER TO RECEIVER DISTANCE (FT)
       BARRIER OPTICAL HEIGHT (FT)

                        SOURCE 1   ?90,30,70,4

    NOISE LEVELS (DBA)                        WATTS/SQ M

  WITHOUT    WITH    SOUND LEVEL        WITHOUT      WITH
  BARRIER   BARRIER   REDUCTION         BARRIER     BARRIER

   84.0      71.1       12.9           .0002500     .0000128

>RUN

 FOR CALCULATIONS USING LINE OF SIGHT DISTANCES
 AND PERPENDICULAR HEIGHTS:                   INPUT 1

 FOR CALCULATIONS USING HORIZONTAL AND VERTICAL
 COORDINATES (TWO DIMENSIONS):                   INPUT 2   ?2


 HOW MANY SOURCES   ?1

 INPUT THE HORIZ AND VERT COORD OF THE BARRIER (FT)   ?30,12

 INPUT THE HORIZ AND VERT COORD OF THE RECEIVER (FT)   ?100,8

 INPUT FOR EACH SOURCE:
       NOISE LEVEL AT 50 FEET (DBA)
       HORIZ COORD OF SOURCE (FT)
       VERT COORD OF SOURCE (FT)

                        SOURCE 1   ?90,0,8

    NOISE LEVELS (DBA)                        WATTS/SQ M

  WITHOUT    WITH    SOUND LEVEL        WITHOUT      WITH
  BARRIER   BARRIER   REDUCTION         BARRIER     BARRIER

   84.0      71.1       12.9           .0002500     .0000128

>
```


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APPENDIX D

Derivation of Truck Noise Model

A noise model was developed to represent the spectral nature of a typical truck noise source. The model is composed of eight incremental sources, each presenting the geometric mean of an octave band.

The model is necessary because rigorous noise diffraction calculations can only be made on discrete frequencies. Diffraction calculations for broad band noises require that the noise be divided into its components and the calculations performed on each component. The resultants can then be summed to obtain a single number answer.

The first step in developing the model was to obtain a series of octave band analyses of truck noise (1). The sound level was then averaged for each octave band. The end result was to reflect the 'A' weighting network so each band was reduced by a suitable factor (2). . The resultants were converted to energy intensity in equivalent watts per square meter for use in the model.

The model, as listed below, consists of eight weighted wattages each acting at the geometric mean frequency of an octave band (2).

Frequency Band (Hz)	Geometric Mean (Hz)	Weighted Acoustical Watts/m^2	Ratio
37.5-75	53	$.126 \times 10^{-6}$	.00072
75-150	106	6.31	.03598
150-300	212	31.6	.18032
300-600	424	50.1	.28579
600-1200	849	39.8	.22701
1200-2400	1700	39.8	.22702
2400-4800	3390	6.3	.03598
4800-10,000	6790	1.2	.00718
	Total	175.4×10^{-6}	1.00000

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To use the model, the sound level in dBA is converted to intensity in weighted acoustical watts per square meter by equation (1D):

$$I = 10^{(dBA/10-12)} \tag{1D}$$

The intensity at each frequency can then be estimated by multiplying the total intensity by the model's ratio for that frequency.

The total wattage at a point can be determined by arithmetically summing the energy intensity arriving at the point from all known sources. The intensity can be converted to dBA by the equation (2D):

$$L = 10 \log_{10}(I) + 120 \tag{2D}$$

As an example, let us consider a truck producing one A weighted acoustical watt per square meter (120 dBA). Assume all the noise is coming from one point in space. For calculation purposes, we would consider the noise to be composed of eight sources: a 53 Hz source of .00072 watts, a 106 Hz source of .03578 watts, etc. If we find it necessary to consider more than the one point source in our model, we must perform calculations on eight times the number of different noise source locations.

References

1. Galloway, W. J.; Clark, W. E.: and Kerrick, J. S.; "Urban Highway Noise: Measurement, Simulation, and Mixed Ractions," NCHRP Report 78 (1969).

2. Rettinger, M., Acoustic Design and Noise Control, Chemical Publishing Co. (1973).

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APPENDIX E

Noise Diffraction Computer Program

The attached computer program can be used to calculate the diffraction of truck noise over a barrier. It is written to be used on the Caltrans TENET time sharing computer service. The program is written in BASIC but FORTRAN versions of the subroutines are also listed.

The program uses the method presented in an issue of Noise Control (Rettinger, 1957). It uses the noise model described in Appendix D. The Fresnel integral subroutine was derived from an article in Mathematics of Computation (1).. The use of the program is described in Appendix C.

The inputs to the FORTRAN subroutine are DBSORC, A, B and H. DBSORC is the loudness of the source as measured in dBA at 50 feet. A, B and H are dimensions as described in Appendix C. The outputs are SUWATT and SAWATT. These are the sums of the unattenuated and attenuated A weighted wattages that are expected at the receiver. The first value is what is expected if the path from the source to the receiver were not impaired. The second value represents the wattage diffracted over the barrier. These wattages can be converted to dBA by the following equation:

$$L = 10 \log_{10} I + 120$$

where L = sound level in dBA
I = sound intensity in equivalent watts per square meter.

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Optimization

This computer program is probably adequate for limited use. It should be optimized, however, before it is used extensively in iterative applications. A large savings in computer time would result from lowering the precision requirements of the Fresnel integral subroutine or otherwise optimizing the Fresnel integral computation.

DEFAULTS

This program will not run to completion if dimensions A or B become negative. It will also terminate when there is underflow in the Fresnel integral subroutine.

References

1. J. Boersma, "Computation of Fresnel Integrals," Math. Comp. 14 (1960 380.

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```
1000      REM     **** ** NOISE DIFFRACTION PROGRAM ******
1010      REM
1020      REM     FOR USE ON THE CALIF DIV. OF HIGHWAYS TENET TIME SHARE
1030      REM     COMPUTER TERMINALS
1040      REM        WRITTEN BY WALT WINTER
1050      REM         REVISED 12/28/71
1060      REM
1070    DOUBLE AFAC(12),BFAC(12),CFAC(12),DFAC(12),
           SUMA,SUMB,X,XFOR,XFAC
1080    DIM FREQ(8),STD(9)
1090      DATA 53,106,212,424,849,1700,3390,6790
1100      DATA 1.259E-07,6.31E-06,3.162E-05,5.012E-05,3.981E-05,
              3.981E-05,6.31E-06,1.259E-06,1.7537E-04
1110      DATA 1.59576914,-1702D-9,-6.808568854,-5763610-9,
            6.920691902,-168986570-9,-3.05048566,-.075752419,
            .850663781,-.025639041,-.15023096,.034404779
1120      DATA -33D-9,4.255387524,-92810D-9,-7.7800204,
            -.009520895,5.075161298,-.138341947,-1.363729124,
            -.403349276,.702222016,-.216195929,.019547031
1130      DATA 0D1,-.024933975,3936D-9,5770956D-9,
            689892D-9,-9497136D-9,.011948809,-.006748873,
            24642D-8,21029670-9,-.00121793,233939D-9
1140      DATA .19947114,23D-9,-.009351341,230060-9,48514660-9,
            .001903218,-.017122914,.029064067,-.027928955,.016497308,
          -.005598515,.000838386
1150     MAT READ FREQ, STD,AFAC,BFAC,CFAC,DFAC
1160     FACT=LOG(10.)
1170     SSUW=0.
1180     SSAW=0.
1190     PRINT
1200     PRINT ' FOR CALCULATIONS USING LINE OF SIGHT DISTANCES'
1210     PRINT ' AND PERPENDICULAR HEIGHTS:                INPUT 1'
1220     PRINT
1230     PRINT ' FOR CALCULATIONS USING HORIZONTAL AND VERTICAL'
1240     PRINT ' COORDINATES (TWO DIMENSIONS):               INPUT 2';
1250     INPUT ICFL
1260     PRINT
1270     PRINT
1280   IF ICFL = 1 THEN 1310
1290   IF ICFL = 2 THEN 1500
1300      GOTO 1190
1310     PRINT ' HOW MANY SOURCES';
1320     INPUT NSRC
1330     PRINT
1340     PRINT ' INPUT FOR EACH SOURCE:'
1350     PRINT TAB(7):'NOISE LEVEL AT 50 FEET (DBA)'
1360     PRINT TAB(7):'SOURCE TO BARRIER DISTANCE (FT)'
1370     PRINT TAB(7):'BARRIER TO RECEIVER DISTANCE (FT)'
1390     PRINT TAB(7):'BARRIER OPTICAL HEIGHT (FT)'
1400  FOR I = 1 TO NSRC
1410     PRINT
1430     PRINT TAB(20+3*I):'SOURCE ':I;
1440     INPUT SP50,A,B,H
1450
          GOSUB 1970 ! CALLING SUBROUTINE ATTENS

1460     SSUW=SSUW+SUW
1470     SSAW=SSAW+SAW
1480  NEXT I
1490     GOTO 1810
```

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```
1500     PRINT ' HOW MANY SOURCES';
1510     INPUT NSRC
1520     PRINT
1530     PRINT ' INPUT THE HORIZ AND VERT COORD OF THE BARRIER (FT)';
1540     INPUT WALX,WALY
1550     PRINT
1560     PRINT ' INPUT THE HORIZ AND VERT COORD OF THE RECEIVER (FT)';
1570     INPUT EARX,EARY
1610     PRINT
1620     PRINT ' INPUT FOR EACH SOURCE:'
1630     PRINT TAB(7):'NOISE LEVEL AT 50 FEET (DBA)'
1640     PRINT TAB(7):'HORIZ COORD OF SOURCE (FT)'
1660     PRINT TAB(7): 'VERT COORD OF SOURCE (FT)'
1670 FOR I = 1 TO NSRC
1680     PRINT
1690     PRINT TAB(20+3*I):'SOURCE ':I;
1695     INPUT SP50,EPX,EPY
1700     AB=SQRT((EARX-EPX)^2+(EARY-EPY)^2)
1710     ANA=ATAN((EARY-EPY)/(EARX-EPX))
1720     ANB=ATAN((WALY-EPY)/(WALX-EPX))
1730     ANC=ANB-ANA
1740     A=SQRT((WALX-EPX)^2+(WALY-EPY)^2)*COS(ANC)
1750     B=AB-A
1760     H=TAN(ANC)*A
1770
          GOSUB 1970 ! CALLING SUBROUTINE ATTENS

1780     SSUW=SSUW+SUW
1790     SSAW=SSAW+SAW
1800 NEXT I
1810     UNAT=10.*LOG(SSUW)/FACT+120.
1820     ATEN=10.*LOG(SSAW)/FACT+120.
1830     SLR=UNAT-ATEN
1840     PRINT
1850     PRINT '      NOISE LEVELS (DBA)                        WATTS/SQ M'
1860     PRINT
1870     PRINT '  WITHOUT    WITH    SOUND LEVEL        WITHOUT       WITH'
1880     PRINT '  BARRIER  BARRIER    REDUCTION         BARRIER      BARRIER'
1890     PRINT
1900     PRINT IN FORM "%%%%%.%BBBBBB%%.%BBBB%%%.%": UNAT,ATEN,SLR;
1910     PRINT IN FORM "BBBBBBB%%%.%%%%%%B%%%%.%%%%%%": SSUW,SSAW
1920     PRINT
1930     PRINT
1940 END
1960 REM
                SUBROUTINE ATTENS

1970      SAW=0.
1980      SUW=0.
1990      AB=A+B
2000      SRCW=EXP((SP50/10-8.535)*FACT)
2010 FOR J=1 TO 8
2020      SRC=SRCW*STD(J)/STD(9)
2030      V=H*SQRT(FREQ(J)*AB/(565.*A*B))
2040
         GOSUB 2120 ! CALLING SUBROUTINE FRESNEL

2050      UWT=SRC/(AB*AB*1.167)
2060      AWT=UWT*((.5-CX)^2+(.5-SX)^2)/2.
2070      SUW=SUW+UWT
```

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```
2080      SAW=SAW+A*T
2090 NEXT J
2100
         RETURN

2110 REM
               SUBROUTINE FRESNEL

2120      X=.5*V*V*3.14159265
2130      SUMB=0.
2140      SUMA=0.
2150      XFAC=1.
2160  IF X>6 THEN 2240
2170      XFOR=X/4.
2180 FOR K = 1 TO 12
2190      SUMA=SUMA+XFAC*AFAC(K)
2200      SUMB=SUMB+XFAC*BFAC(K)
2210      XFAC=XFAC*XFOR
2220 NEXT K
2230       GOTO 2300
2240      XFOR=4/X
2250 FOR K=1 TO 12
2260      SUMA=SUMA+XFAC*CFAC(K)
2270      SUMB=SUMB+XFAC*DFAC(K)
2280      XFAC=XFAC*XFOR
2290 NEXT K
2300      XFOR=SQRT(XFOR)
2310      SUMA=SUMA*XFOR
2320      SUMB=SUMB*XFOR
2330      CX=COS(X)*SUMA+SIN(X)*SUMB
2340      SX=SIN(X)*SUMA-COS(X)*SUMB
2350  IF X < 6 THEN 2380
2360      CX=CX+.5
2370      SX=SX+.5
2380  IF V >= 0 THEN 2410
2390      CX=-CX
2400      SX=-SX
2410        RETURN

2420 END
>
```

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```
      SUBROUTINE ATTENS

      COMMON DBSORC, A,B,H,SUWATT,SAWATT

            DIMENSION FREQ(8),STD(9)
            DATA FREQ/53.,106.,212.,424.,849.,1700.,3390.,6790./
            DATA STD/1.259E-07,6.31E-06,3.162E-05,5.012E-05,3.981E-05,
                  3.981E-05,6.31E-06,1.259E-06,1.7537E-04/

            SAWATT=0.
            SUWATT=0.
            AB=A+B
            WATT50=10.**((DBSORC+34.4794)/10.-12.)
      DO 40 J=1,8
            SOURCE=WATT50*STD(J)/STD(9)
            V=H*SQRT(FREQ(J)*AB/(565.*A*B))

            CALL FRESNL(V,CX,SX)

            UWATTS=SOURCE/(AB*AB*1.22)
            AWATTS=UWATTS*((.5-CX)**2+(.5-SX)**2)/2.
            SUWATT=SUWATT+UWATTS
            SAWATT=SAWATT+AWATTS
      40 CONTINUE

      RETURN
      END
```

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```
      SUBROUTINE FRESNL(V,CX,SX)
      DOUBLE PRECISION AFAC(12),BFAC(12),CFAC(12),DFAC(12),
     *     SUMA,SUMB,X,XFOR,XFAC
      DATA AFAC/1.59576914,-1702D-9,-6.808568854,-576361D-9,
     *     6.920691902,-16898657D-9,-3.05048566,-.075752419,
     *     .850663781,-.025639041,-.15023096,.034404779/
      DATA BFAC/-33D-9,4.255387524,-92810D-9,-7.7800204,
     *     -.009520895,5.075161298,-.138341947,-1.363729124,
     *     -.403349276,.702222016,-.216195929,.019547031/
      DATA CFAC/0D1,-.024933975,3936D-9,5770956D-9,
     *     689892D-9,-9497136D-9,.011948809,-.006748873,
     *     24642D-8,2102967D-9,-.00121793,233939D-9/
      DATA DFAC/.19947114,23D-9,-.009351341,23006D-9,4851466D-9,
     *     .001903218,-.017122914,.029064067,-.027928955,.016497308,
     *     -.005598515,.000838386/
      X=.5*V*V*3.14159265
        SUMB=0.
        SUMA=0.
        XFAC=1.
       IF (X .GT. 6.) GOTO 4
        XFOR=X/4.
      DO 2 J=1,12
        SUMA=SUMA+XFAC*AFAC(J)
        SUMB=SUMB+XFAC*BFAC(J)
    2 XFAC=XFAC*XFOR
          GOTO 8
    4 XFOR=4./X
      DO 6 J=1,12
        SUMA=SUMA+XFAC*CFAC(J)
        SUMB=SUMB+XFAC*DFAC(J)
    6 XFAC=XFAC*XFOR
    8 XFOR=SQRT(XFOR)
        SUMA=SUMA*XFOR
        SUMB=SUMB*XFOR
        CX=DCOS(X)*SUMA+DSIN(X)*SUMB
        SX=DSIN(X)*SUMA-DCOS(X)*SUMB
       IF (X .LE. 6.) GOTO 10
        CX=CX+.5
        SX=SX+.5
   10 IF (V .GE. 0.) GOTO 12
        CX=-CX
        SX=-SX
   12 RETURN
      END
```

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